On the Role of SST Forcing in the 2011 and 2012 Extreme U.S. Heat and Drought: A Study in Contrasts

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Submitted to the *Journal of Hydrometeorology Special Collection on "Advancing Drought Monitoring and Prediction"*

26 April 2013

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ABSTRACT

This study compares the extreme heat and drought that developed over the United States in 2011 and 2012 with a focus on the role of SST forcing. Experiments with the NASA GEOS-5 atmospheric general circulation model show that the winter/spring response over the U.S. to the Pacific SST is remarkably similar for the two years despite substantial differences in the tropical Pacific SST. As such, the pronounced winter and early spring temperature differences between the two years (warmth confined to the south in 2011 and covering much of the continent in 2012) primarily reflect differences in the contributions from the Atlantic and Indian Oceans, with both acting to cool the east and upper mid-west during 2011, while during 2012 the Indian Ocean reinforced the Pacific-driven continental-wide warming and the Atlantic played a less important role. During late spring and summer of 2011 the tropical Pacific SST force a continued warming and drying over the southern U.S., though considerably weaker than observed. Nevertheless, the observed anomalies fall within the model's intra-ensemble spread. In contrast, the rapid development of intense heat and drying over the central U.S. during June and July of 2012 falls outside the model's intra-ensemble spread. The response to the SST (a northward expansion of a modest summer warming linked to the Atlantic) gives little indication that 2012 would produce record-breaking precipitation deficits and heat in the central Great Plains. A diagnosis of the 2012 observed circulation anomalies shows that the most extreme heat and drought was tied to the development of a stationary Rossby wave and an associated anomalous upper tropospheric high maintained by weather transients.

1. Introduction

Throughout its history, the United States (U.S.) has experienced numerous droughts and heat waves, and these have caused extensive human suffering and enormous economic loss. The last few decades have seen significant advances in our understanding of large-scale controls on these droughts. In particular, it is now well known that certain spatial patterns of Sea Surface Temperature (SST) are conducive to generating precipitation deficits or meteorological droughts over much of the continent. Examples of such SST patterns include those associated with the El Niño – Southern Oscillation (ENSO) on seasonal-to-interannual time scales and those associated with the Pacific Decadal Oscillation (PDO), and the Atlantic Multi-decadal Oscillation (AMO), on decadal and longer timescales.

The impacts of these SST patterns over the U.S. and the physical mechanisms by which they act have been extensively studied using observations (e.g. Ting and Wang 1997; Nigam et al. 2011; Hu and Feng 2012; Dai 2012) and Atmospheric General Circulation Model (AGCM) simulations (e.g., Hoerling and Kumar 2003; Schubert et al. 2004a and b; Seager et al. 2005; Wang et al 2010). An important finding from such studies is that ENSO and the PDO in their cold phases, and the AMO in its warm phase, produce a tendency for drought conditions over the U.S., with the Pacific playing the dominant role (e.g., Mo et al. 2009; Schubert et al. 2009). In addition, the impact of SST anomalies over the U.S. varies substantially from region to region. While droughts over the southern Plains and southwestern U.S. are significantly promoted by certain tropical SST anomalies and appear to have some predictability on seasonal time scales, the droughts over the northern Plains are more strongly determined by atmospheric internal variability and appear to be less predictable (Hoerling et al 2009).

While certain SST patterns can be important in initiating drought and determining the timing of the drought, sustaining and/or amplifying droughts over the U.S. involves other factors such as local soil moisture feedback and random atmospheric internal variability (e.g. Koster et al. 2003; Ferguson et al. 2010). For example, a month with low precipitation leads to a drier-than-average soil which in turn can lead to lower-than-average evaporation, which may lead to continued low precipitation. Such feedback between the land and atmosphere plays an important role in the development and continuation of droughts over the U.S., particularly during the warm season and over the central part of the country (Koster et al. 2006). There is also evidence that extended droughts can lead to heat waves in the following months (Mueller and Seneviratne 2012).

Recently, the U.S. again experienced severe drought and heat events. Drought and heat waves encompassed the southern U.S. (especially Texas) and northern Mexico (hereafter the Tex-Mex region) during the summer of 2011 (e.g., Seager et al. 2013), while during the summer of 2012, intense drought and heat anomalies were seen in the central Plains (e.g. Hoerling et al. 2013). Figure 1 shows surface temperature, precipitation and surface soil wetness[4] anomalies from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) land (Reichle et al, 2011, 2012)[5] during the years 2011-2012. (Note: care must be taken in the interpretation of the MERRA-Land soil moistures presented here, which are model products rather than true observations, which do not exist at these scales. Although MERRA-Land soil wetness anomalies should represent the real-world anomalies reasonably well, the modeled values also reflect

[4] This is the degree of saturation in the top 2 cm of the soil (values range from 0 to 1).

[5] MERRA-Land is a land-only replay of MERRA-Land model component, with the precipitation forcing based on merging a gauge-based data product from the NOAA Climate Prediction Center with MERRA precipitation, and an updated version of the NASA GEOS-5 catchment land surface model.

various model assumptions affecting soil moisture persistence.) Figure 1 shows that the 2011 U.S. drought mainly occurred over the Tex-Mex region, characterized by strong surface warming anomalies and by severe deficits in precipitation and surface soil wetness. During the preceding winter, while there were cooling anomalies over the majority of the U.S., the precipitation and surface soil wetness anomalies showed some indications of dry conditions along the southern and southeastern U.S. Such dry anomalies were enhanced in the spring, apparently facilitating drought development. The 2011 drought and heat wave over the southern Great Plains were at maximum strength during June and persisted through the rest of the summer. By comparison, the 2012 summer drought and heat wave mainly occurred over the central Great Plains, and peaked during July 2012. In contrast with 2011, the preceding winter and early spring were unusually warm over much of the continent, especially during March 2012 when numerous records were set (Dole et al. 2012). The abnormally warm surface condition in the preceding cold seasons led to the presence of very little snow during the spring, though it is unclear whether this contributed to the development of the summer drought (see section 3.3).

The substantial differences in the record heat and drought that developed over the United States during 2011 and 2012 offer an important opportunity to assess further the differing roles of SST forcing in the development of such extreme events. The 2011 and 2012 U.S. droughts were accompanied by SST anomalies that had important similarities as well as some differences. Figure 2[6] shows that La Nina conditions existed in the tropical Pacific during the winter of 2010/2011 and that these gradually decayed during the spring and summer, though with somewhat of a resurgence going into the winter of 2012; La Nina conditions decayed quickly

[6] The ENSO-MEI (Wolter and Timlin 2011), PDO (Zhang et al 1997) and AMO (Enfield et al 2001) indices were obtained from http://www.esrl.noaa.gov/psd/enso/mei/table.html, http://jisao.washington.edu/pdo/PDO.latest, and http://www.esrl.noaa.gov/psd/data/correlation/amon.us.data, respectively.

after that. Thus, whereas the summer of 2011 still showed some remnants of the La Nina with cold anomalies over the central tropical Pacific, these remnants were largely gone during the summer of 2012, with the eastern tropical Pacific showing signs of a developing warm event. Common features of both summers were a cold PDO and warm AMO, with the cold PDO being stronger in 2011 and the warm AMO more prominent during 2012.

The objective of this study is to investigate the roles played by SST forcing in the evolution of the 2011 and 2012 U.S. summer droughts. We include an analysis of SST impacts during the preceding winter and spring, with the idea that the influence of winter and spring anomalies can perhaps persist into the warm season via mechanisms involving land processes and land-atmosphere feedback. The analysis is based primarily on a series of AGCM experiments designed to isolate the impacts of SST anomalies in different ocean basins. The AGCM used in this study is the National Aeronautics and Space Administration Goddard Earth Observing System Model, Version 5 (GEOS-5), as documented by Rienecker et al. (2008).

The paper is organized as follows. The description of the observational (reanalysis) data, the GEOS-5 AGCM, and the model experiments is given in Section 2. Section 3 presents the results from a suite of AGCM experiments, as well as, from some limited simulations with the atmosphere-ocean coupled version of the GEOS-5 model. The discussion and conclusions are provided in Section 4.

2. **Model Experiments**

a) Reanalysis

The Reanalysis data consist of 3-hourly and monthly MERRA data (Rienecker et al 2011) and monthly MERRA-Land data (Reichle et al 2011, 2012) for the period January 1979 – August 2012. The MERRA data are used primarily to describe the atmospheric circulation. The surface air temperature, precipitation and surface soil wetness fields from MERRA-Land are used to describe the 2011 and 2012 droughts. We note that MERRA-Land precipitation estimates are, by construction, consistent with Global Precipitation Climatology Project (GPCP) observations (Huffman et al. 2009). Temperature anomalies in MERRA-Land are consistent with various observational estimates (not shown).

b) The GEOS-5 Model

The GEOS-5 AGCM (Rienecker *et al.*, 2008, Molod *et al.*, 2012) employs the finite-volume dynamics of Lin (2004) and various moist physics packages described in Bacmeister *et al.* (2006) including: a modified form of the Relaxed Arakawa-Schubert convection scheme (Moorthi and Suarez, 1992) with stochastic Tokioka limits on plume entrainment (Tokioka et al 1988), a prognostic cloud microphysics scheme (Bacmeister *et al.* 2006), and the Catchment Land Surface Model (Koster *et al.*, 2000). Molod et al. (2012) show that GEOS-5 AGCM simulation results generally agree well with observational estimates. Relevant to this study, the GEOS-5 AGCM deficiencies during boreal summer include a dry bias over the U.S. Great Plains, along with weaker-than-observed upper-tropospheric zonal wind and transients in the Northern Hemisphere (NH) middle latitudes. The potential implications of the dry bias for the interpretation of our results will be discussed in subsequent sections.

We will also show some limited results from the coupled GEOS-5 atmosphere-ocean general circulation model (AOGCM) seasonal forecasts. With the AOGCM (Vernieres et al. 2012), SST

fields are not prescribed but are rather provided by the MOM4 ocean model (Griffies et al. 2005).

c) The GEOS-5 AGCM Experiments

Most of our results in this study are derived from a series of GEOS-5 AGCM (Rienecker et al. 2008) experiments forced with prescribed SST. The experiments consist of simulations covering the period January 1979-August 2012, as well as shorter-term AGCM experiments for the years 2011 and 2012. All of the AGCM experiments were run at 1-degree latitude/longitude horizontal resolution with 72 vertical levels.

The GEOS-5 simulations over the period January 1979 – February 2010[7] (referred to hereafter as our baseline simulations) were forced with monthly SST and ice fraction data obtained from Hurrell et al (2008), which are available up to March 2010. For the period March 2010 - present, the GEOS-5 simulations were forced with the NOAA Optimum Interpolation (OI) weekly SST v2 (Reynolds et al 2002). The use of different SST and ice fraction products over different periods in our AGCM runs does not notably affect our results (not shown). The baseline simulations consist of 12 members, among which 10 use Goddard Chemistry Aerosol Radiation and Transport (GOCART) aerosols, and 2 use parameterized (PCHEM) aerosols. Again, the use of different aerosol fields does not noticeably affect the monthly means of the variables examined here.

Numerous short-term GEOS-5 AGCM experiments were performed for both 2011 and 2012. One experiment consists of a 20-member ensemble initialized on 15 November of the previous

[7] We note that these runs were actually started in 1870, so there is no memory of the initial conditions for the recent decades.

year (2010 or 2011) and forced with global SST anomalies. These ensembles were then repeated several times, using climatological SSTs (from the period 1980-2010) everywhere but in selected regions of interest; in separate ensembles, we prescribed realistic SSTs only in: (i) the tropical Pacific (30ºS-25ºN), (ii) the north Pacific (25ºN-65ºN), (iii) the tropical Atlantic (30ºS-25ºN), and (iv) the north Atlantic (25ºN-65ºN). Another set of short-term experiments were initialized November 1 for a focus on the wintertime response to Pacific, Atlantic and Indian Ocean SSTs.

For these shorter simulations, the atmospheric and land initial conditions were taken from November of different years of the baseline runs. The early start date provides the spin-up time needed to avoid any transient adjustments that the model might make in response to the initialization. Spin-up issues are further alleviated by taking initial conditions from the baseline simulations rather than from observational data such as MERRA, helping us to isolate better the SST impacts on simulated drought. The 20 ensemble members in a given experiment differ from each other only in their atmospheric and land initial conditions. In order to construct a useful climatology for the short-term experiments (to allow the computation of anomalies for 2011 and 2012), we also performed a set of AGCM runs for each year from 1980 through 2010, with one member per year. The atmospheric and land initial conditions for these runs were again taken from the baseline simulations.

3. Results

3.1. The Response to Global SST Forcing

We begin by evaluating how well the 2011 and 2012 heat waves and droughts are represented in the baseline simulations forced with the observed global SSTs. Our comparison begins with a look at the ensemble means. The ensemble average reduces the unforced atmospheric internal

variability and highlights those signals forced by the SSTs. Comparisons between MERRA and the model simulations must therefore be made with the understanding that the observational estimates are themselves a mix of forced (by SST) and unforced variability – i.e., that the signals contained in the ensemble means will be, by their very nature, smoothed out and potentially less extreme than those seen in the observations. To address this, we also examine the model's intra ensemble variability.

Figure 3 shows the 12-member ensemble mean results of the baseline model simulations. One of the most striking aspects of the comparison with MERRA-Land (Figure 1) is that the model reproduces the pronounced differences between the two winters discussed earlier, with 2012 showing a continental wide warming, while during 2011 the warming (if any) was confined to the Gulf states. The results during summer, on the other hand, are not as accurate. The ensemble mean does not reproduce the intensification of the heat and precipitation deficits over Texas during the summer of 2011, showing primarily an expansion of the warming and drying signal beginning in July, with soil wetness deficits covering much of the central part of the country by the end of summer. The ensemble mean of the simulations also does not reproduce the observed intense heat and record-breaking precipitation deficits (and associated soil wetness anomalies) that developed over the Central Plains in 2012 during late spring and summer, with the ensemble mean showing only a weak warming that develops in the central and northern plains in July and August, with little contribution from soil wetness anomalies.

Figure 4 shows the January-August time series of surface temperature, precipitation and surface soil wetness anomalies for the 12 individual ensemble members and the observations (MERRA-Land) averaged over the southern Great Plains in 2011 (upper panels) and central Great Plains in 2012 (lower panels). The upper panels show that for 2011, with the exception of summertime

precipitation, the observational estimates generally fall within the spread of the 12 ensemble members. In contrast, during 2012, the observed summer anomalies of all three variables (most prominently the June precipitation) fall outside the model spread. The soil wetness anomalies further illustrate the key differences between the two years, with all ensemble members showing drying throughout 2011 (an indication of a strong SST influence in the southern Great Plains), but with only weak drying (on average) over the Central Plains during 2012 along with considerable ensemble spread that includes some members that are getting wetter. The strongest impact of SST in 2012 over the central Plains appears to be on the temperature; the overall warming signal is especially strong in late winter.

As already mentioned the free-running AGCM does have a dry bias over the Great Plains, so some of the differences with respect to MERRA-Land may simply reflect that model deficiency. To minimize that problem, we present the anomalies as percentiles (relative to each data set's underlying distribution) in Figure 5. In terms of percentiles, the observational estimates generally do fall within the model spread for both winters and for the summer of 2011, but they remain outside the spread for the summer of 2012. This suggests that the model is deficient in simulating key processes important for the development of the record extremes of 2012, though it could also be true that the ensemble size is simply too small to span a realistic spread that could encompass more extreme events. In either case, the model results indicate that the 2012 summer anomalies reflect a very extreme and rare event that was unlikely to have been strongly induced by SST distributions. This will be investigated further in Section 3.3.

3.2. The Response to Regional SST Forcing

In view of the stronger impact of the SST on U.S. surface temperature (compared with precipitation), our analysis of the roles of the different ocean basins will focus primarily on how they influence temperature. We will begin with an examination of the different SST forcing of the 2011 and 2012 cold seasons. We will then turn to the late spring and summer seasons.

3.2.1. Winter/Early Spring (JFM)

Figure 6 shows the ensemble mean results of two sets (for 2011 and 2012) of 20 AGCM simulations initialized at the beginning of the previous November. The results (top panels) confirm what we saw with our baseline AGCM runs for JFM: the largest positive surface temperature anomalies are confined to the southern U.S. during 2011, and they span the continental U.S. and parts of Canada during 2012. The 250mb height anomalies (bottom panels) also show distinct differences over the U.S.. A weak positive height anomaly extends from the Pacific eastward across the southern U.S. during 2011, and a substantially stronger positive height anomaly covers much of the U.S. during 2012, with the latter being part of a large positive anomaly that extends from the U.S. northeastwards into northern Europe. Overall, the height anomalies during 2012 appear to be a combination of a positive North Atlantic Oscillation (NAO) and a Pacific-North American (PNA)-like wave response. In contrast, during 2011, the anomalies over the North Atlantic resemble those of a negative NAO, while over the Pacific there is a strong tropical response, with weaker and smaller-scale north-south oriented anomalies in the North Pacific/North American region.

Figure 7 shows the results from the additional 20-member ensembles in which the AGCM was forced with SSTs from individual (Pacific, Atlantic and Indian) Ocean basins, with climatological SST elsewhere. A key result is the remarkable similarity between years in the

U.S. surface temperature response to the Pacific SST (left panels a and b), with warming encompassing the entire U.S. continent during both years. The height response (right panels a and b) is also quite similar over the U.S., despite a much stronger response over the Pacific during 2011. We must therefore look to the other oceans to explain the differences over the U.S. between the two years. In particular, we see (left panels c and e) that the Atlantic (middle row panels) and Indian (bottom row panels) SST distributions act to confine the positive surface temperature anomalies to the southern Great Plains during 2011, since they both induce negative surface temperature anomalies over the northern Great Plains and the eastern U.S.. These effects are associated with negative NAO-like responses to SST in both oceans (right panels c and e). In contrast, during 2012 the Indian Ocean acts to reinforce the warming from the Pacific (left panel f), and the Atlantic Ocean, while still inducing negative temperature anomalies over the eastern U.S., plays a less important role (left panel d).

We note that the above temperature responses over the U.S. are remarkably linear in the sense that the sum of the responses to the individual ocean basins are a good approximation to the response to the global SST fields (not shown). We now turn to an analysis of the warm season.

3.2.2. Late Spring and Summer

We saw in Section 3.1 that the impact of SST during spring and summer is rather modest, though stronger for surface temperature than for other variables, and stronger for 2011 than for 2012. Here, we dissect that modest impact on surface temperature over the U.S. into contributions from the different ocean basins, with a particular focus on the impacts of the Pacific and Atlantic Oceans – the key contributors to U.S. drought during the warm season, as determined from previous studies (e.g., Schubert et al. 2004b; McCabe et al. 2004; Seager et al. 2005; Mo et al.

2009; Schubert et al. 2009). The results are based on several additional sets of 20 AMIP-style simulations for 2011 and 2012 (initialized in the middle of the previous November) in which the SST anomalies are specified globally (in the control ensemble), or confined to the tropical Pacific, north Pacific, tropical Atlantic, or north Atlantic, with climatological SST elsewhere.

Figure 8 shows the results for 2011. Consistent with the baseline simulations (Figure 3), the response to global SST anomalies (leftmost column) shows surface warming anomalies over the southern U.S. during April and May. The warming anomalies expand northward into the central plains in June, and subsequently expand to occupy much of the U.S. by the end of the summer. The responses to the regional SST anomalies indicate that the surface warming anomalies over the southern U.S. from April to June 2011 are mainly forced by the SST anomalies in the tropical Pacific. The north Pacific has little impact. The contribution from the tropical Atlantic sets in during June and is the main driver behind the surface warming anomalies over the central and northern U.S. during July, with some contribution also from the north Atlantic. During August, the tropical Atlantic SST anomalies contribute to surface warming over the western U.S., and the north Atlantic SST anomalies continue to contribute to surface warming over the central and northern plains.

Figure 9 is the same as Figure 8 but for 2012. The surface temperature responses to global SST anomalies are again consistent with those in the baseline simulations. The one exception is April, for which the current 20-member ensemble confines the anomalies more to the south and west, compared to the baseline runs which have the anomalies covering most of the U.S.; this difference likely reflects differences in early springtime land conditions, as well as possible sampling errors.

Looking at the impacts of the individual ocean basins we find that the tropical Pacific (second column in Fig. 9) plays a predominant role in defining U.S. temperature anomalies from early 2012 to the early part of summer, whereas the tropical Atlantic (fourth column) and north Atlantic (fifth column) take over in importance for the central and western Plains during the second half of the summer 2012. This behavior is similar to that seen in Figure 8 for 2011.

The upper panel of Figure 10 summarizes the impacts of the regional SST anomalies on surface temperature averaged over the southern Great Plains from January to August of 2011. The results highlight the important role of the tropical Pacific in forcing surface warming over that region in early 2011, as well as during the first half of the summer. During the latter half of the summer, the SST anomalies in the tropical and north Atlantic reinforce each other to warm the region. These results further emphasize that the development of the 2011 heat wave was driven by SST anomalies in both the Pacific and Atlantic, with the different timing of the impacts acting to extend the warm conditions throughout the warm season. The lower panel of Figure 10 is the same as the upper, but for the central Plains during 2012. As in early 2011, the tropical Pacific SST during 2012 contributed to surface warming over the southern U.S. during the winter and early spring, whereas the warm Atlantic contributed to a weak surface warming over the central U.S. during the latter half of the summer.

In summary, the timing of the impacts of the ocean basins on U.S. temperature anomalies is similar in the two years. We have already seen (Fig. 7) that the cold season response to SST is linked to large-scale changes in the stationary waves, with the response to the Pacific associated with a PNA-like response and the response to the Atlantic resembling an NAO-like structure. During the summer the warming and drying over the U.S. associated with the Atlantic (and Pacific) SST tends to be associated with more of a zonally-symmetric response in the upper

tropospheric height field (e.g., Schubert et al. 2002; Kumar et al. 2003) as well as a low level response that impacts the moisture transported from the Gulf of Mexico (e.g., Schubert et al. 2009; Wang et al. 2010; Hoerling et al. 2013).

While the Pacific produced a predilection for warming over the U.S. during both years, and while the Atlantic appears to be instrumental in continuing the warming over the central plains in summer, the SSTs by themselves do not explain the development of the extremes, especially the sudden development of the 2012 heat wave and drought. In the following we look at the processes involved in the development of the 2012 heat wave and drought in more detail, with an eye toward identifying potential connections between the 2011 and 2012 events.

3.3. Are the 2011 and 2012 Summer Heat and Drought Events Connected?

In assessing potential links between the 2011 and 2012 events, we focus in particular on determining if persistence of 2011 dry soil conditions into 2012 contributed to the development of the 2012 drought. We also look more directly at the physical processes involved in the forcing and maintenance of the atmospheric circulation anomalies that developed during the 2012 summer.

3.3.1 Role of soil moisture

The evolution of the soil wetness anomalies in Figure 1 gives little indication that the dry conditions that developed in May and June of 2012 are a continuation of pre-existing dry soil conditions (see also Hoerling et al. 2013). In fact, the first 4 months of 2012 had near normal if not slightly above normal rainfall in the central and upper Great Plains, and soil wetness was near normal going in to April, with the exception of a region in the upper Midwest that could have played a role in the subsequent development of anomalies in May. Figure 11 addresses this

possibility, showing results from a suite of seasonal forecasts with the GEOS-5 coupled model initialized in early May, June and July[8] of 2012. For these runs, the atmosphere is initialized from MERRA, the ocean from the GEOS-5 ocean analysis (Vernieres et al. 2012), and the land from an off-line calculation in which the land model is forced with observations-based meteorological forcing, including precipitation fields tied to rain gauge measurements.

While the forecasts starting in May (top left panel of Fig. 11) do predict warm anomalies for July in the Great Plains (extending northwestward into Canada), any sense of the severity of the 2012 event is not predicted until the next set of forecasts, which start in June. The forecasts starting in July finally pick up on the breadth of the event (third top panel from left). The forecasted signal is even less clear for precipitation (bottom row of Figure 11). While the forecasts starting in May and June predict small precipitation deficits for July over parts of the Great Plains, only the forecasts starting in July capture the full strength of these deficits. If dry soil moisture conditions from 2011 (Figure 1) persisting into 2012 did contribute significantly to the 2012 drought, we would expect the forecasts (which take advantage of such information) to capture this. The overall sense of the forecast results, however, is that while the dry conditions perhaps contributed in some way to the development of the July temperature anomalies, they did not contribute significantly to the initiation of the severe record-breaking precipitation deficits of that summer.

The above results must however be tempered by the fact that the GEOS-5 model has a dry bias over the Great Plains, so that we could be underestimating the role of soil moisture deficits. With the dry bias, there may be little room for further drying of the soil and subsequent feedback on the precipitation. Some sense of the impact of the land is given in Figure 12, which shows

[8] The actual start dates for the ensemble members are as follows: For the early May starts the initial conditions are on Apr11, Apr16, Apr21, Apr26, May01, May06, with May01 having 5 members. For the early June starts the initial states are on May11, May16, May21, May26, May31, with the Jun30 starts having 7 members. For the early July starts the initial conditions are on Jun10, Jun15, Jun20, Jun25, Jun30, with 7 members on June 30.

the evolution of 2012 conditions in two different ensemble members. One ensemble member (#6) is shown because it comes into spring with extremely warm March conditions rivaling those found in MERRA, though these conditions are quickly dissipated in the following months, with little support from dry land conditions or subsequence precipitation deficits. This simulation's behavior supports the idea that the extremely warm March in nature did not have a major impact on the subsequent development of the summer extremes. The other ensemble member (#4) shows large soil wetness deficits in March over the west and Midwest that are amplified and expanded in June to include much of the central U.S. due to a May precipitation deficit over the central and northern part of the country. Those soil wetness deficits are similar in magnitude to those found in nature (as estimated from MERRA-Land –Figure 1), and they continue into July and August. However, unlike in MERRA, the precipitation deficits do not continue much beyond June, suggesting a low degree of soil moisture feedback on precipitation.

The effect of soil moisture feedback on 2012 conditions was addressed further with some additional AGCM experiments (not shown). In these experiments, the feedback was artificially disabled – seasonal cycles of climatological soil moisture (obtained by averaging 3-hourly soil moisture from a set of short-term hindcast runs for years 1980 through 2010) was continuously prescribed at the land surface. These experiments, when compared to those with interactive land, show that soil moisture feedback is critical for amplifying the SST-forced warm summer surface temperature anomalies during both years. The effect of the feedback on precipitation, however, is significantly less.

3.3.2 Development and maintenance of the 2012 summer anomalies

The development of the May precipitation deficits over the central and northern Plains in ensemble member four (Figure 12) is found to be associated with the development of a stationary Rossby wave (not shown). Schubert et al. (2011) show that such waves have played a key role in the development of some of the most extreme heat waves and droughts over the U.S.. In this subsection we take a closer look at the evolution and maintenance of the atmospheric circulation anomalies associated with the 2012 event to assess whether such waves also played a role here.

Figure 13 shows the evolution of the daily Ts and precipitation anomalies over the U.S. together with the (10-day running mean) evolution of the upper level meridional wind and height field. The longitude/time hovmöller diagrams (values averaged between 34°N and 46°N) show considerable week to week variability in the evolution of both Ts and precipitation, with however the most intense and persistent positive anomalies in Ts developing over the central U.S. in mid June, lasting well into August. This was accompanied by sustained precipitation deficits that lasted into late August. The wind and height anomalies also show rather unorganized variability on weekly time scales with however the signature of a well define wave train the propagates eastward from the Pacific impacting the central U.S. in the second half of June, with some evidence of a phase locking and persistence of the wave resulting in positive height anomalies over the central U.S throughout July. A second wave train develops during August producing negative height anomalies over the U.S., and that appears linked with negative temperature anomalies and an alleviation of the central U.S. precipitation deficits in late August.

The above results are consistent with an important role for summertime Rossby waves in the development and evolution of the main precipitation and temperature anomalies over the central Great Plains during the summer of 2012. This is further bolstered by the results of a stationary wave model diagnosis (not shown), indicating that the positive height anomalies over the U.S.

are maintained by submonthly (primarily vorticity) transients, the primary forcing of summertime stationary Rossby waves (Schubert et al. 2011). One therefore gets the impression of an unfolding of a series of events during the summer of 2012 that are primarily driven by internal atmospheric dynamics, which together produced one of the most severe droughts on record over the central U.S.. In fact, Hoerling et al. (2013) concluded that the drought was the result of “a sequence of unfortunate events”. While our results are generally in agreement with that assessment, Fig. 14 suggests that the sequence of events may have developed in a large-scale environment favoring a predilection for warm temperatures and precipitation deficits. That environment consists of weak but positive height anomalies that extend around the globe in the middle latitudes of both hemispheres. The similarity between the baseline model response and the MERRA anomalies suggests that they are largely SST forced. Furthermore, the global nature of the response suggests the possibility of simultaneous drought in various regions, for example, it makes the fact that the Eurasian grain belt also suffered from drought and heat during that summer, somewhat less of a coincidence.

Coming back to the comparison with 2011, we note that the same type of zonally-symmetric response occurred in the model for that summer, though slightly shifted to the south compared with 2012 (not shown). That response was in this case, however, not reflected in the observations (MERRA), which showed instead a strong negative expression of the Artic Oscillation[9] that appears to have in part masked the SST-forced signal.

4. Discussion and Conclusions

[9] http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/month.ao.gif

The United States experienced record-breaking drought and heat during both 2011 and 2012. The location and overall evolution of the temperature and precipitation anomalies in the two years, however, show substantial differences. The 2011 anomalies largely reflect what is now a generally well-understood response to cold tropical Pacific (La Nina) SSTs in primarily the southern Great Plains (especially Texas and Northern Mexico, e.g., Seager et al. 2013). In contrast, the 2012 anomalies were rather atypical, with unusual warmth spanning the entire continent during the winter and early spring, followed by a rapid development (during May and June) of record-breaking precipitation deficits and extreme temperatures over the central Plains – a region believed not to be strongly affected by remote SST forcing during the warm season.

GEOS-5 AGCM simulations forced with observed SSTs are consistent with observations for 2011, with the ensemble mean showing warming and drying generally confined to the south for the first half of the year. Although the intensification of the drought and heat over Texas during the summer of 2011 was not captured in the ensemble mean and thus appears to be unforced by SST, the observed summertime temperature and precipitation extremes fell within the spread of the model's ensemble. The model also reproduced the unusual 2012 winter and early spring warmth that extended across much of the continent. The model, however, failed to reproduce the rapid development of intense heat and drying over the central U.S. during June and July of 2012, with the observed anomalies falling outside the model's intra-ensemble spread.

The above model results were analyzed further by performing additional experiments in which the prescription of observed SSTs was confined to individual ocean basins or sub-basins, with climatological SSTs prescribed elsewhere. These results showed that during the cold season the Pacific SSTs produce a general warming over the U.S. that is remarkably similar for the two

years, despite the near absence of La Nina conditions during 2012; this indicates that the SSTs associated with a negative Pacific Decadal Oscillation (common to both years) played a key role during both cold seasons. We found also that the pronounced temperature differences between the two years (warmth confined to the south in 2011 as opposed to covering much of the continent in 2012) primarily reflect differences in the contributions from the Atlantic and Indian Oceans; during 2011, both basins acted to cool the east and upper mid-west, whereas during 2012, the Indian Ocean reinforced the Pacific-driven continental-wide warming, and the Atlantic Ocean's contribution was less important. These results are not inconsistent with the Hoerling et al. (2004) study, which found that a warm Indian Ocean forces a positive polarity of the NAO. Such an impact from the Indian Ocean, however, does not appear in all models. For example, Seager et al. (2013) found that neither CCM3 nor ECHAM4.5 showed a significant impact on the NAO from the SST forcing in the winter of 2010/11, suggesting that the occurrence of the negative NAO during that winter was instead largely an example of unforced internal atmospheric variability.

The response over the U.S. to Atlantic SST anomalies is consistent with the impacts found over the eastern U.S. by Lim and Schubert (2011). Our results are also not inconsistent with the study of Dole et al. (2012), who found that the March 2012 heat anomaly in particular was the result of enhanced northward transport of warm air from the Gulf of Mexico, part of a global teleconnection pattern forced by tropical heating associated with La Nina SST anomalies and a strong MJO. We indeed find that some of our ensemble members have the most intense heating anomalies in March (not shown), indicating that internal atmospheric variability did play an important role, though our results show that the Indian Ocean contributed as well. Whether the Pacific Ocean's contribution is associated with La Nina or the negative PDO may be largely an

issue of definition. Pinpointing the precise aspects of Pacific SST that truly matter for the U.S. will require additional research.

During late spring and early summer of both years the tropical Pacific forces heat and drought conditions over the southern Plains; this is followed in both years by a northward expansion of a modest warming in mid-summer tied primarily to forcing from the Atlantic. This seasonality in response to the Pacific and Atlantic SSTs reflects the seasonal changes in the mean flow -- the Pacific Ocean modifies stationary waves in late spring and early summer, whereas the Atlantic (and Pacific) SST affect the inflow of moisture from the Gulf of Mexico during mid and late summer. Schubert et al. (2009) and Wang et al. (2010) found that such seasonality in the responses to Pacific and Atlantic SSTs can be expected even with a seasonally unvarying SST forcing, indicating that the changes largely reflect the dependence of the SST response on seasonal changes in mean stationary waves, low level winds, and so on.

There is little evidence from the model simulations to suggest that the development of the 2012 extreme summer heat and drought in the central Plains was significantly promoted by antecedent dry soil conditions, say from the preceding year of drought. Nevertheless, the experiments in which we disabled soil moisture feedback suggest that once drought conditions developed in 2012, land-atmosphere feedbacks contributed substantially to the intensity of the heat. The apparent impacts of feedback on the precipitation deficits were much smaller.

A diagnosis of the observed summer circulation anomalies over the U.S. shows that the most extreme heat and drought during late June and July of 2012 was associated with the development of an anomalous upper tropospheric high over the central and northern U.S., and this was linked to the development of a Rossby wave and maintained by weather transients. Overall, our results

regarding the rapid development of the 2012 summer drought provide additional support to the multi-model analysis of this event by Hoerling et al. (2013) indicating that atmospheric internal variability was the basic cause, and that any contribution from SST forcing was rather small. We should emphasize that our results indicate that the intensity of the 2011 summer drought conditions over the Tex/Mex region was also strongly tied to internal atmospheric variability, consistent with the findings of Seager et al. (2013). This highlights the importance of atmospheric variability in the development of the most extreme short-term drought and heat wave events in general over the U.S. (e.g., the role of Rossby waves, Schubert et al. 2011), though we would argue that it played a greater role in 2012 than in 2011.

Finally, we need to emphasize that all our conclusions regarding the relative importance of atmospheric variability are made with the caveat that model deficiencies (e.g., the dry bias of the GEOS-5 AGCM over the Great Plains) may contribute to an underestimation of the impact of other factors especially the contribution of land feedbacks that could be very important in amplifying even a weak SST-forced signal in the precipitation.

Acknowledgements:

This study was supported by the NOAA Modeling, Analysis, Predictions and Projections (MAPP) program, and the NASA Modeling, Analysis and Prediction (MAP) Program.

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Figure Captions:

Figure 1: The development of 2011 and 2012 U.S. droughts in MERRA-Land: surface temperature (left, units: °K), precipitation (middle, units: mm/day), and surface soil wetness (right, dimensionless degree of saturation in the top 2 cm) anomalies. The anomalies are obtained as deviations from climatology over the period 1980-2010.

Figure 2. Right panels: Observed seasonal mean Sea Surface Temperature (SST) anomalies (unit: K) from HadISST (Rayner et al. 2003) during 2011 and 2012. Anomalies are the deviations from the 1980-2010 climatology. Left panels: Indices of ENSO, the PDO and the AMO for the period January 2010 to August 2012.

Figure 3: The ensemble mean of the GEOS-5 AGCM baseline simulations of the 2011 and 2012 U.S. droughts: surface temperature (left, units: °K), precipitation (middle, units: mm/day), and surface soil wetness (right, dimensionless degree of saturation in the top 2 cm) anomalies. The anomalies are obtained as deviations from climatology over the period 1980-2010.

Figure 4: The comparison between MERRA-Land (red line), the 12 members of the GEOS-5 AGCM baseline simulations (gray lines) and their ensemble mean (black line) for surface temperature (left panels), precipitation (middle panels) and surface soil wetness (right panels) anomalies averaged over southern Great Plains (upper panels) during January-August 2011, and over central Great Plains (lower panels) during January-August 2012.

Figure 5: Same as Figure 4, except for percentiles.

Figure 6: Top panels: JFM ensemble mean response to global SST based on an ensemble of 20 AGCM simulations initialized on Nov 1 of the previous year. Top panels are for 2 meter

temperature (°C) and bottom panels are for 250mb height (meters). Left panels are for 2011 and right panels are for 2012 (computed with respect to the 1980-2010 mean).

Figure 7: Same as Figure 6, but for the responses to the individual ocean basins. Left set of panels are for 2 meter temperature and right set of panels are for 250mb height. Tope panels are for Pacific SST, middle panels are for Atlantic SST, and bottom panels are for Indian Ocean SST.

Figure 8: Roles of regional SST anomalies in the development of surface temperature anomalies associated with the 2011 U.S. drought. The surface temperature anomalies were obtained as deviations from a set of hindcast runs with the same initialized date over the years 1980-2010. Units: °K.

Figure 9: Same as Figure 8, but for 2012.

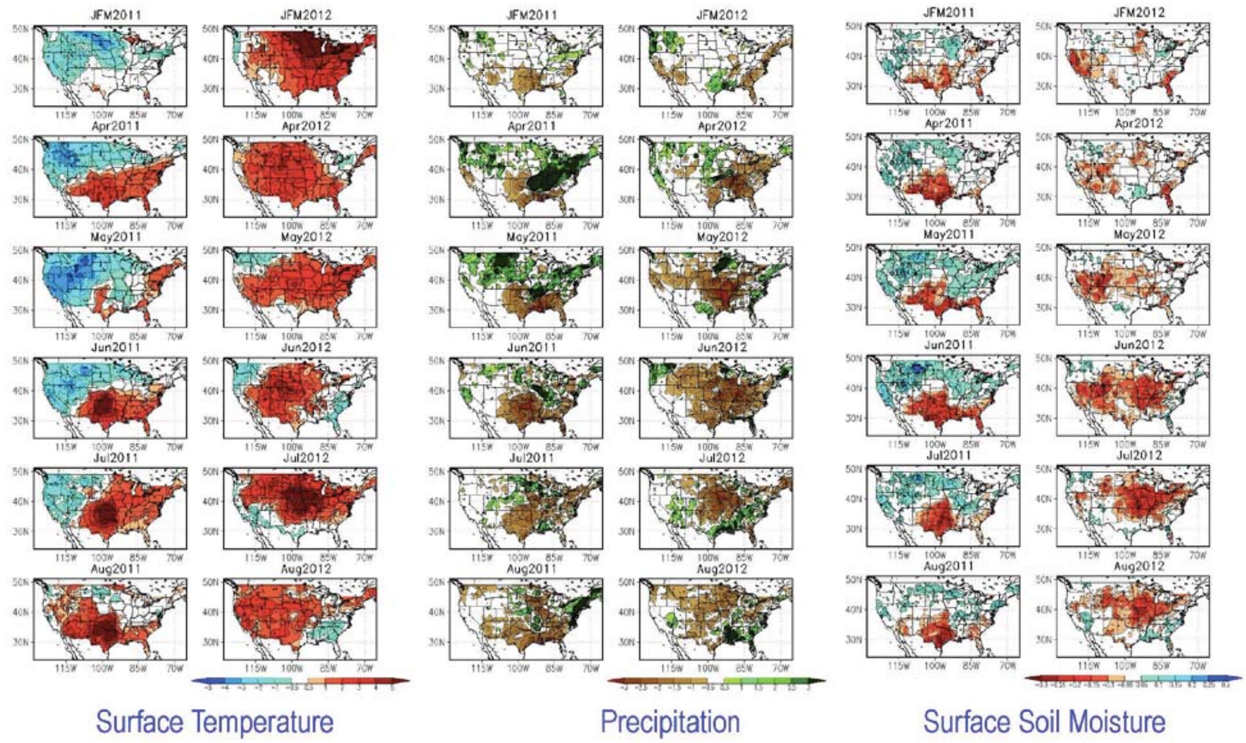
Figure 10: January-August evolution of the affect of SST anomalies in different ocean basins on surface temperature anomalies averaged over the southern Great Plains(252-270°E, 30-42°N) during 2011 (upper panel) and the central Great Plains (252-275E, 33-50°N) during 2012 (lower panel). Values have a 10-day running mean applied. Units: °K.

Figure 11: Top row: July surface temperature anomalies (ensemble means) produced in GEOS-5 coupled model forecasts initialized in early May (first column), early June (second column), and early July (third column) of 2012. The last column shows the results from MERRA. Bottom row: Same as top row but for precipitation. Units are °C and mm/day, respectively.

Figure 12: March through August 2012 evolution of monthly surface temperature (left panels), precipitation (center panels), and surface soil wetness (right panels) for two different ensemble members.

Figure 13: Evolution of the daily Ts (°C, left panel) and precipitation (mm/day, second from left) anomalies averaged between 34N-46N. The 250mb v-wind (m/s, third from left) and height (meters, far right) anomalies are averaged between 35N-50N and have a 10-day running mean smoother applied.

Figure 14: The 2012 MJJA 250mb height anomalies with respect to the 1980-2010 mean. The top panel is from MERRA. The bottom panel shows the ensemble mean of 12 AMIP simulations with the GEOS-AGCM forced with observed SST. Units are meters.



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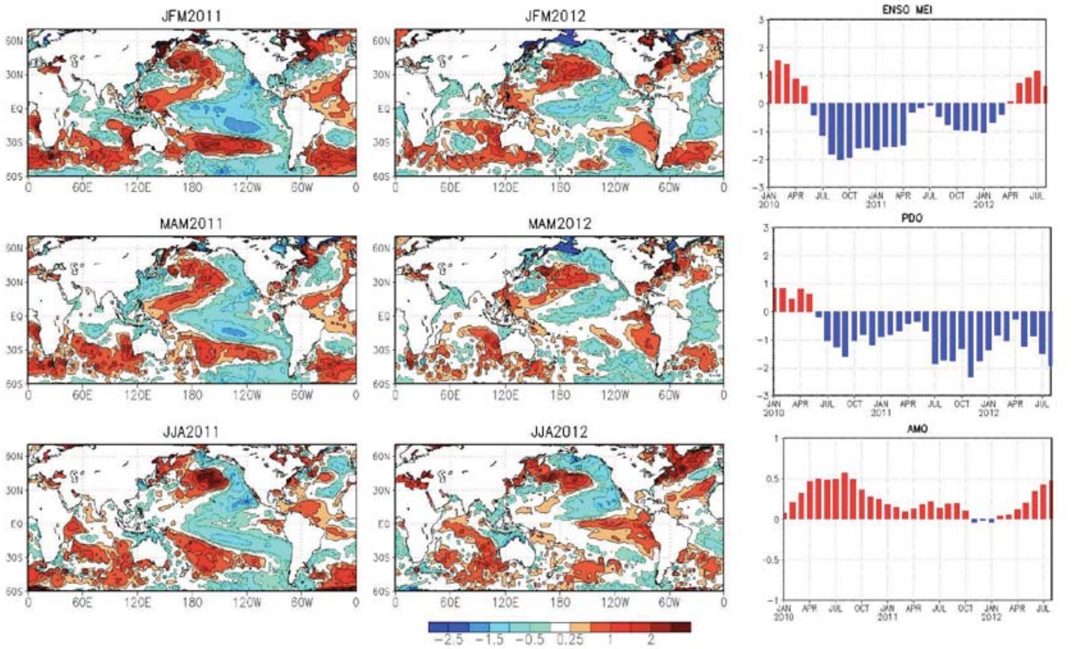

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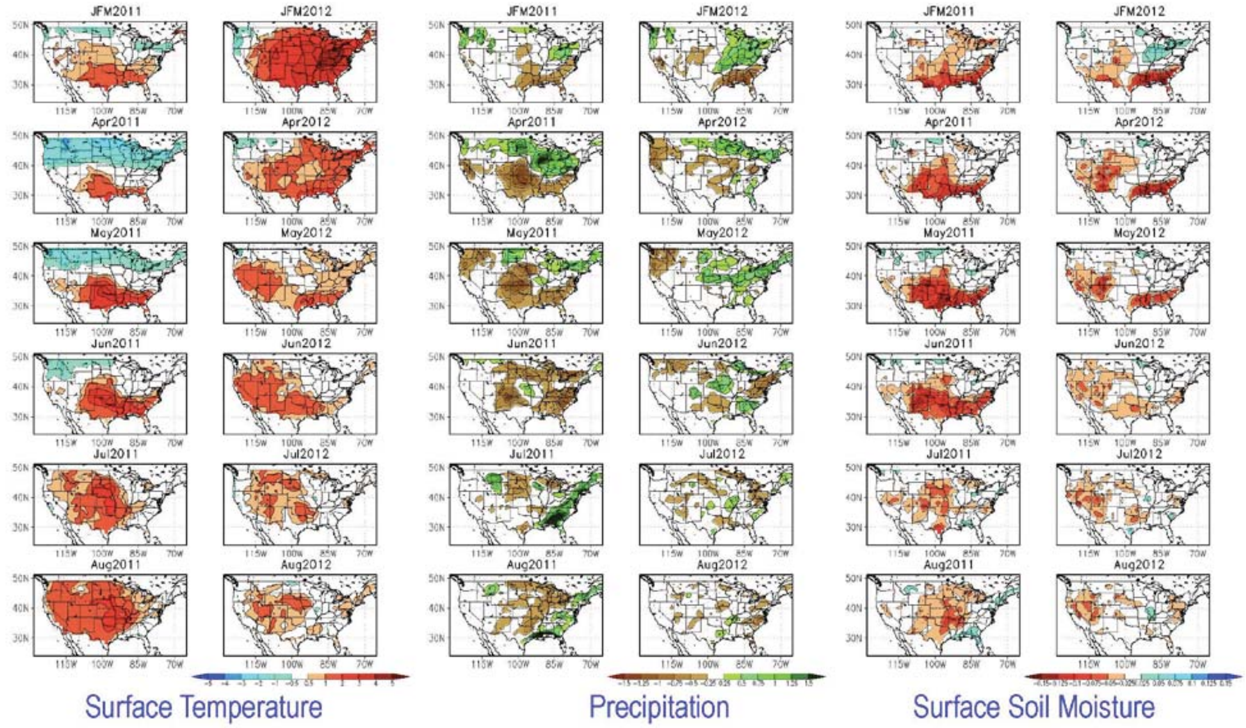

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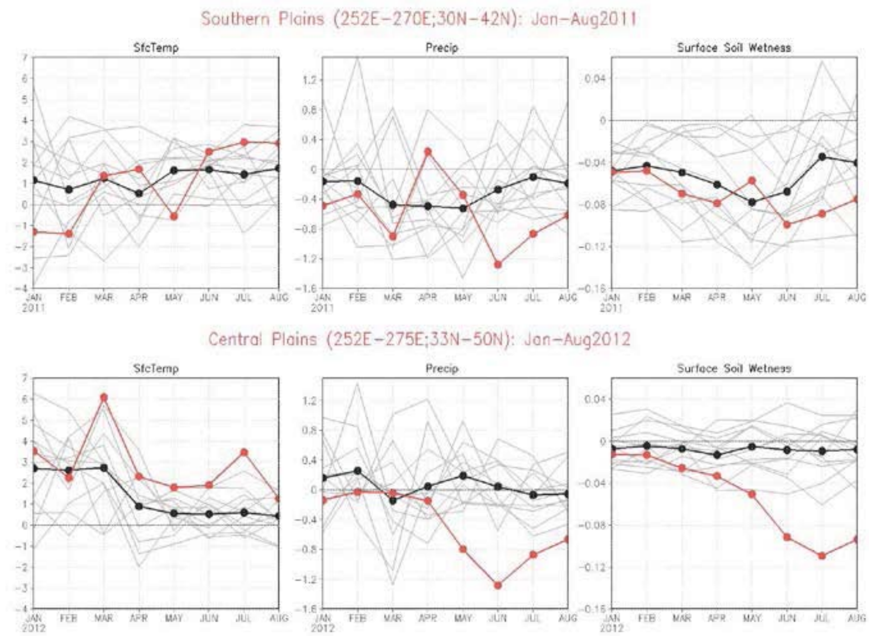

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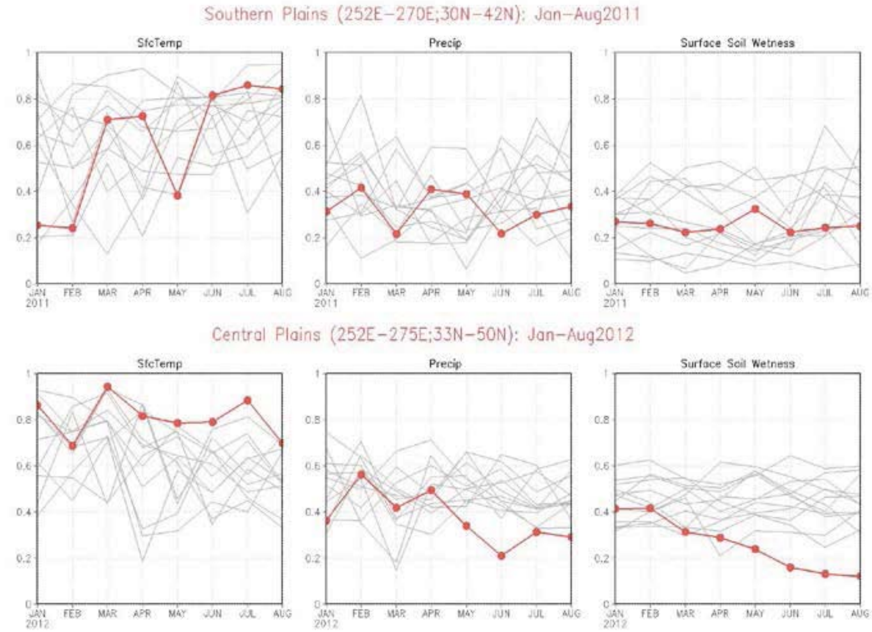

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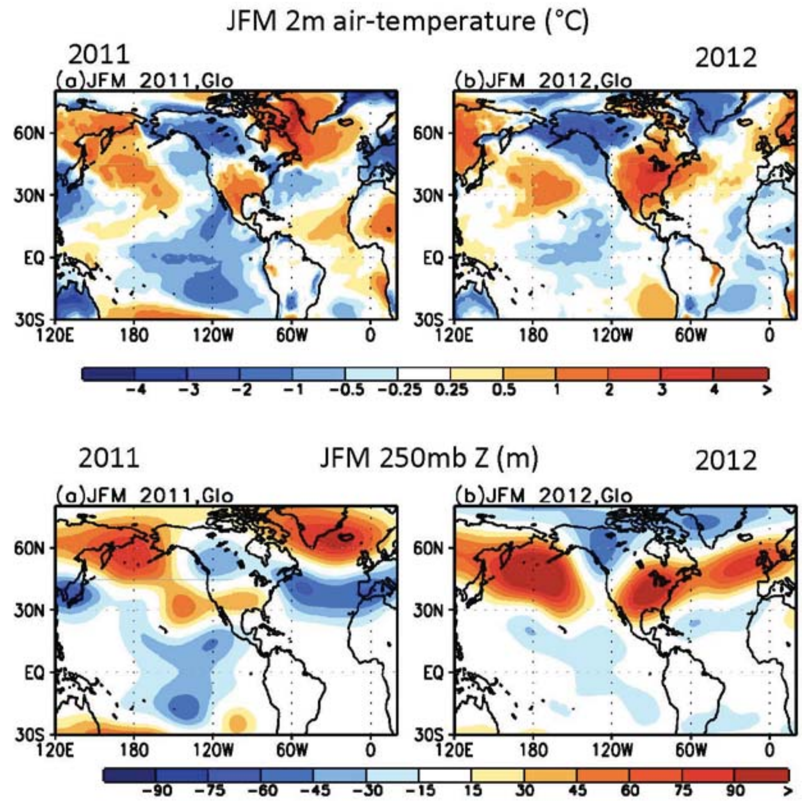

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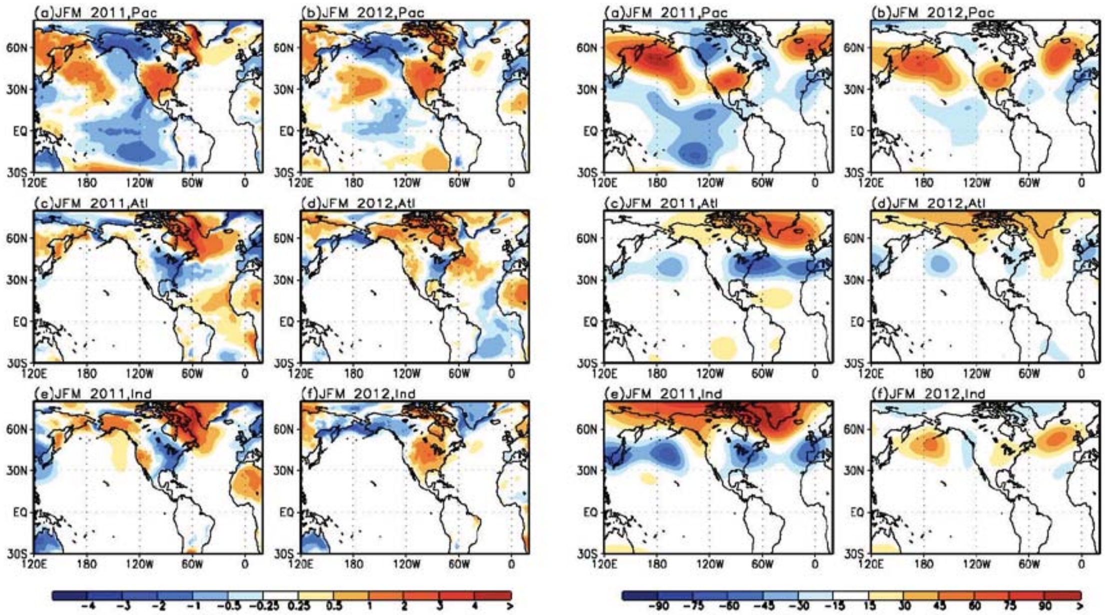

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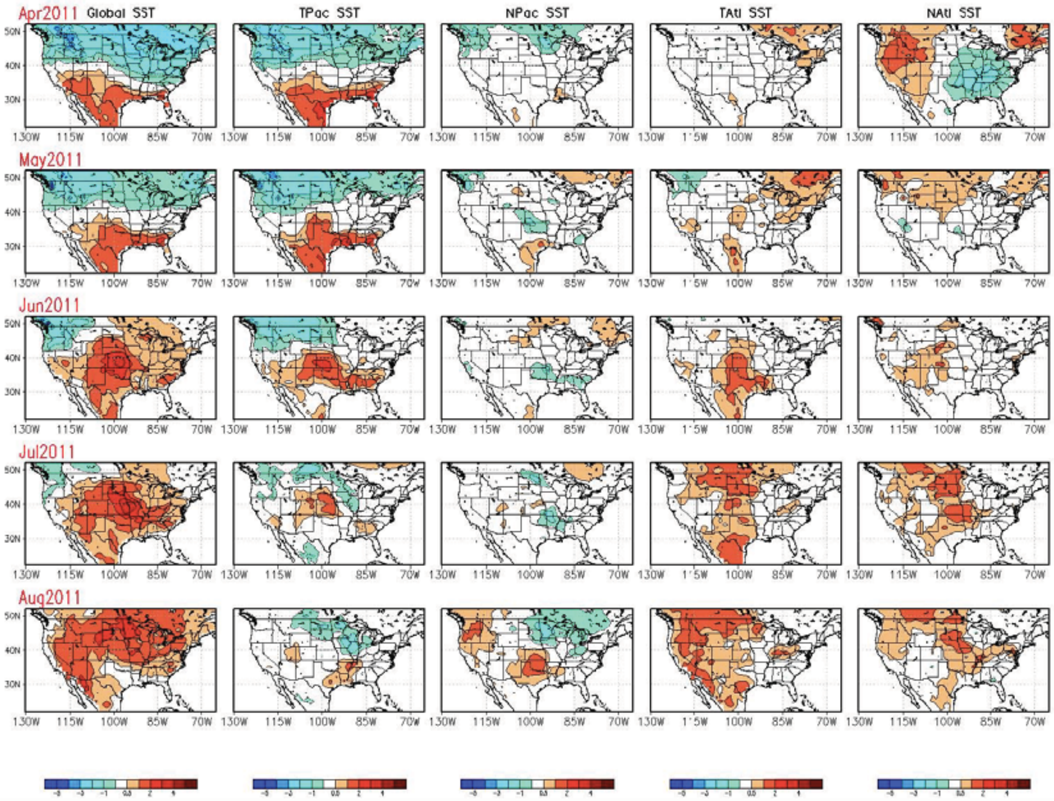

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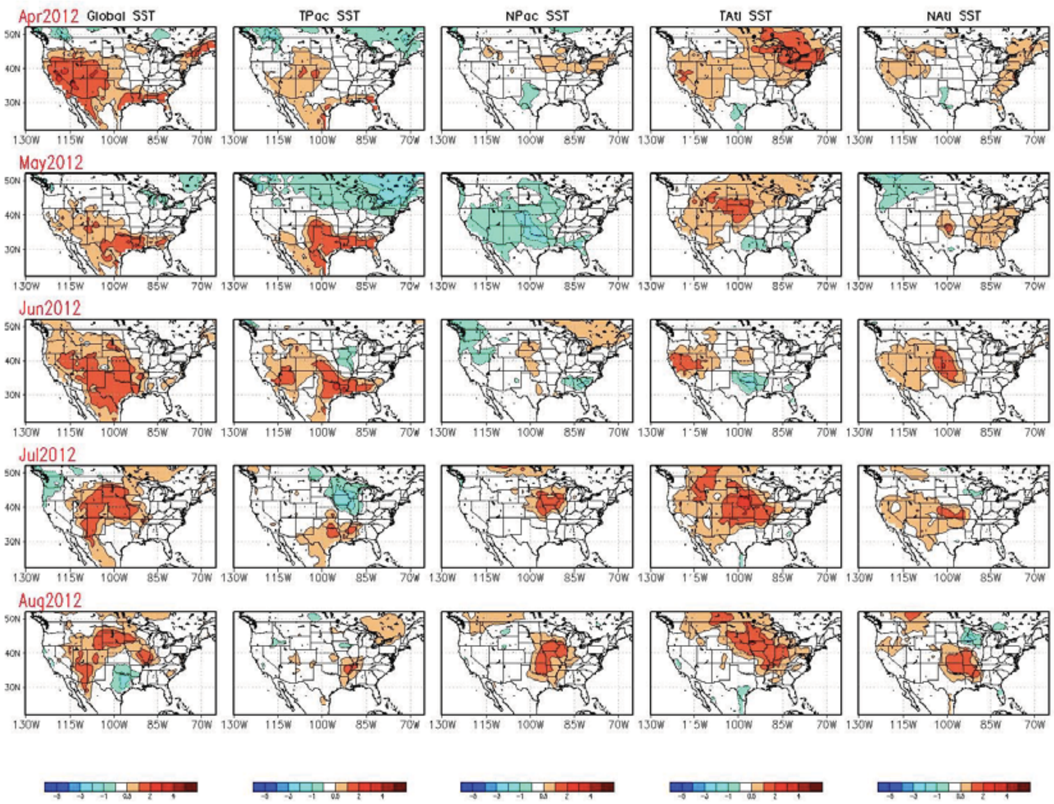

Figure 9: Same as Figure 8 but for the 2012 U.S. drought.

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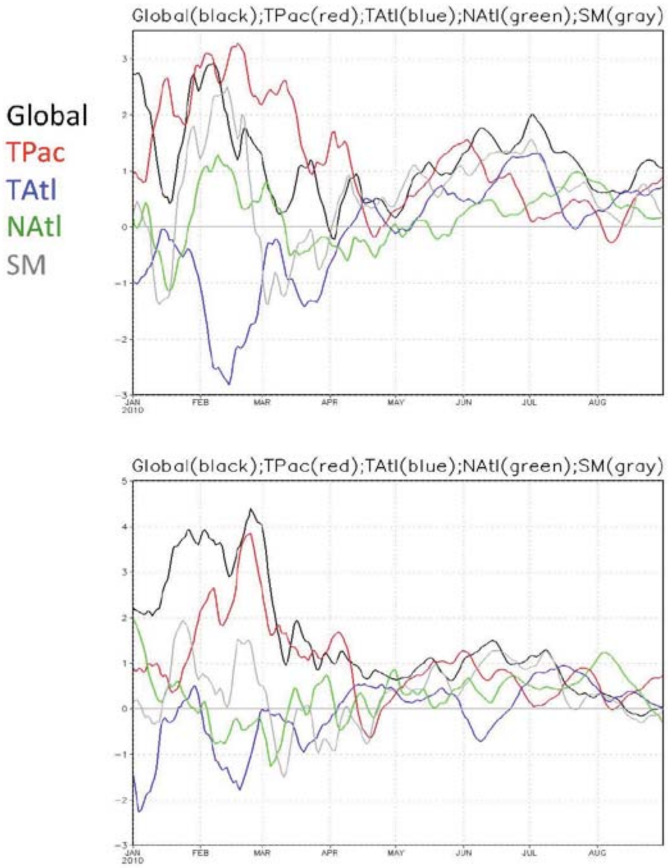

Figure 10: Roles of regional SST anomalies and land feedback for the development of surface temperature anomalies associated with the 2011 (upper panel) and 2012 (lower panel) droughts. Unit: K.

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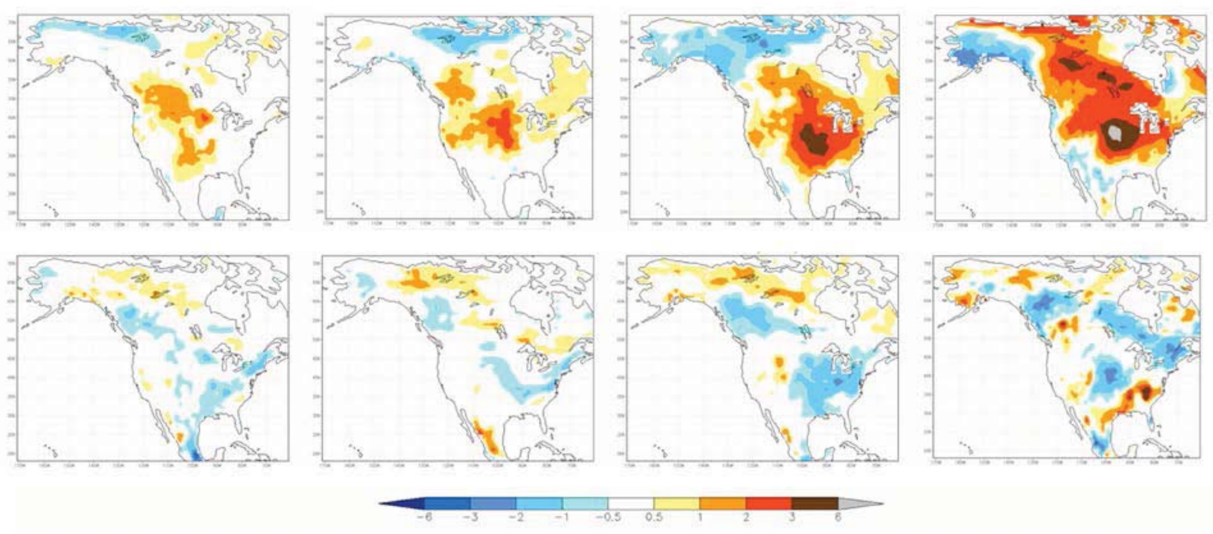

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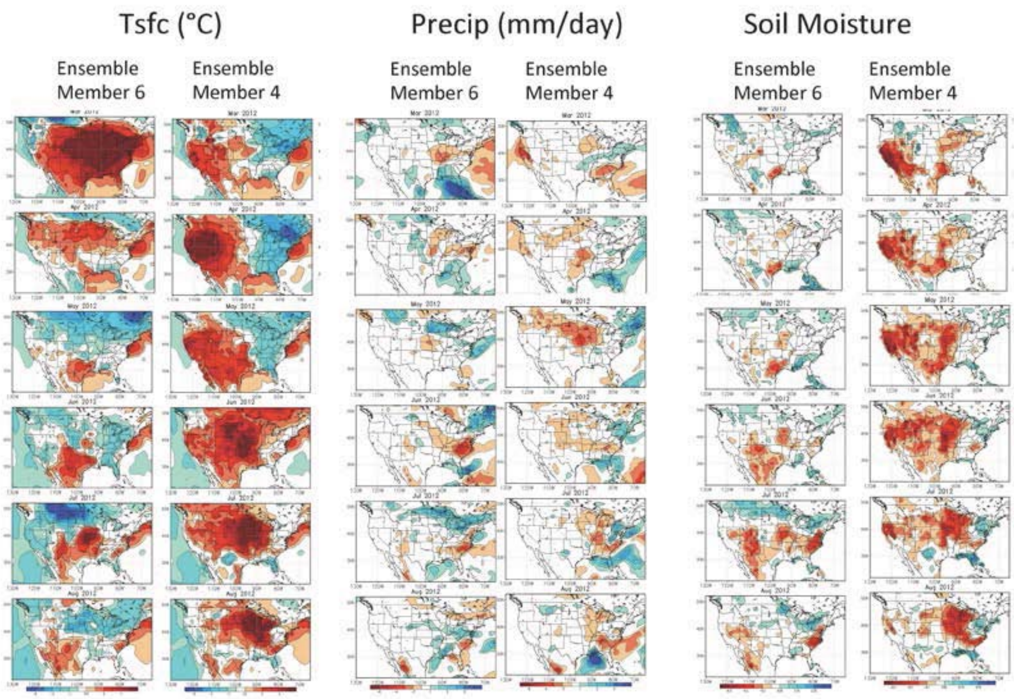

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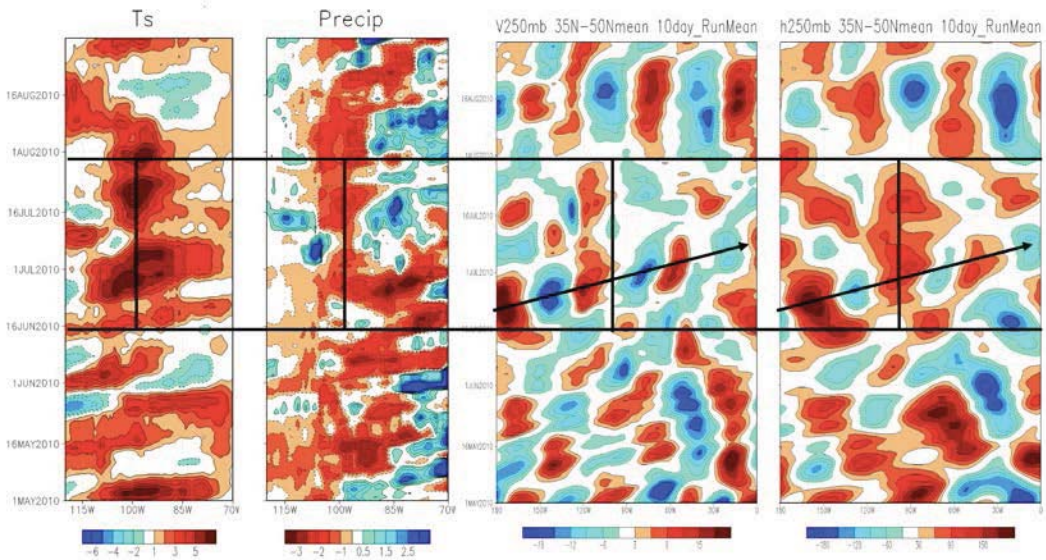

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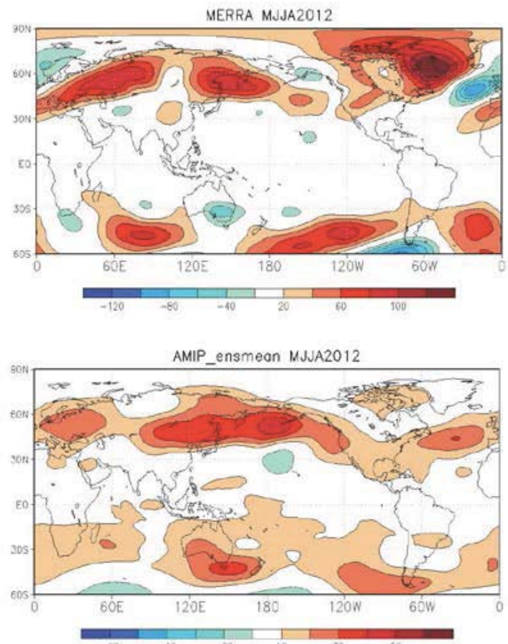

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